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Cold forge spot-bonding of high tensile strength steel and aluminum alloy sheets

Yuri Miwada[a,]*, Takahiro Ishiguro[a], Eiji Abe[a], Nobuki Yukawa[a], Takashi Ishikawa[a], Tomoaki Suganuma[b]

[a]*Department of Material Science and Engineernig, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601,Japan*
[b]*Chubu Reikan Co., Ltd., 13-1 Azawatarijima, Nemunoki-chi, Okazaki, Aichi 444-0232, Japan*

Abstract

Recently automobile components need to have various characteristics that are hard to be fulfilled using a single material for satisfying the several demands like weight saving, cost cutting and crash safety with trade-off relationship. Thus bonding or joining methods of dissimilar materials are necessary. However it is difficult to weld steel and aluminum together. Therefore the authors developed an alternative solid phase bonding method "spot-bonding". In this method, the plastic deformation by cold forging would enable metallic bonding of two dissimilar metals. In this study, this method was applied to bonding of 590MPa-class high tensile strength steel and A2017P aluminum alloy sheets. The joint strength was measured by cross tension testing. When the amount of punch indentation is increased, the joint strength became higher. With the same depth of punch indentation as the total thickness, the joint was broken in the steel base metal blank but not at the interface. Finite element analysis was performed in order to consider the deformation behavior during the bonding process. The parameters on the bonding interface such as surface expansion ratio, surface pressure and relative slippage of two blanks became larger with increase in amount of punch indentation. Furthermore, the bonded region was predicted by calculating the total friction work and the evaluation factor of real contact area that depended on surface expansion and surface pressure.

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Keywords: Cold forging; Bonding; High tensile strength steel sheet; Aluminum alloy sheet; FEM analysis

1. Introduction

Weight saving, cost cutting and crash safety with a trade-off relationship are the most important issues in the

* Corresponding author. Tel.: +81-52-789-3300; fax: +81-52-789-3574.
E-mail address: miwada@p4.numse.nagoya-u.ac.jp

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automobile industry in regards to global environmental problems. Furthermore recent automobile components need to have various characteristics that are hard to be fulfilled using a single material, such as strength, stiffness, corrosion resistance, heat resistance and magnetic properties. Therefore the expectation for hybrid material structure that dissimilar materials with various properties are arranged in specific parts of the structure has increased recently. For example in designing the lightest steel-aluminum hybrid structure, steel is applied to some parts that require strength, stiffness or magnetism, and aluminum alloy is applied to other parts for making structure lightweight. Accordingly, bonding or joining methods of dissimilar metals are necessary.

Brown et al. (1995) showed that the utilization of aluminum in automobile body sheet was started in the early 1970s, but it was restricted to some parts because of poor formability and high cost. As the forming technology improved, most of the automobile manufacturers fabricated aluminum products such as heat exchangers. In some companies all aluminum body was manufactured, but it was expensive. Kelkar et al. (2001) claimed that it is not necessarily the best way that all steel parts in automobiles are substituted for aluminum because of technological and economic disadvantages of aluminum. Therefore the hybrid construction that utilizes aluminum optimally is required. In recent models, aluminum and steel hybrid construction was applied in which aluminum was utilized for space frames. However, in case of utilizing aluminum alloy on steel structure, bonding or joining methods are required. It is difficult to weld steel and aluminum alloy together because of large difference between their melting points and thermal conductivities. Moreover Watanabe et al. (2006) demonstrated that aluminum to steel bond interface includes brittle intermetallic compound layer that consists of Fe_2Al_5 and ($FeAl_2$ + FeAl). The appearance of the layer is a problem in resistant spot welding. When the thickness of the layer is increased, the joint strength is decreased. Therefore mechanical joining with combination components like rivets, bolts and nuts are utilized mainly. However the working cost comes high because of increase in combination components and processes such as drilling. Hence, at present, the several joining processes utilizing plastic deformation is developed and they were summarized by Mori et al. (2013). Plastic deformation could be used to join parts without the external heat supply and the use of plastic deformation for joining parts offers accuracy improvement, reliability and environmental safety as well as creating opportunities to design new products through joining dissimilar materials. For example, in mechanical clinching, sheets are joined by local hemming with a punch and die. Abe et al. (2012) investigated that the mechanical clinching process for high strength steel and aluminum alloy sheets and found that the joinability was improved by the optimization of die shape.

The authors developed an alternative bonding method of spot-bonding in which the plastic deformation by cold forging would enable metallic bonding of two dissimilar metals. The new method is not a joint using fastening tools but a bond at the interface like diffusion bonding. The authors (Miwada et al., 2013) investigated the bonding of steel for general structure and pure aluminum sheet by utilizing the spot-bonding method and confirmed that the steel and aluminum joint had enough breaking strength capable of causing the breakage of aluminum base metal. In this paper this spot-bonding method was applied to bonding of high tensile strength steel and aluminum alloy sheet. The joint strength and efficiencies were measured by performing the cross tension testing on a plurality of specimens changing a working condition. The facture surfaces were investigated on scanning electron microscope (SEM). Besides the behaviors of the materials during forging were simulated by finite element analysis and a parameter that can estimate bonded region on contact surface was proposed.

Nomenclature

F_{MAX}	maximum load value during cross tension testing
m	friction share factor
μ	friction coefficient
A	the initial area of the surface
A_0	the final area of the surface
r	radial distance from the center line
S_{Al}	surface expansion ratio of lower aluminum alloy blank
p	surface pressure
x	relative slippage of two blanks
v	relative sliding velocity of two blanks

W	total friction work
Π	evaluation factor of real contact surface
$\sigma_{0.2}$	0.2 % proof stress of aluminum alloy

2. Spot-bonding

Bay (1983) demonstrated that bonding of the two metals at room temperature is created by plastic deformation like rolling or compressing and examined the bonding theoretical model of Al-Al cold compression welding using surface pressure and surface expansion as parameters. The authors (Ishikawa et al., 2010) developed the backward extrusion process to form and join two layered cylindrical cup of steel and aluminum alloy and found that surface pressure and surface expansion are necessary to obtain to strong bonding in cold forge bonding. In this study, the joining method of dissimilar metal sheets in cold forging process was developed utilizing this knowledge.

Spot-bonding is a method of extrusion used for joining metal sheets. Two blanks, one is steel and the other is aluminum alloy, were sandwiched between a blank holder and a bottom die. A plastic-deformable and disposable metal blank, hereafter referred to as deforming die, is seated between the lower blank and the bottom die, as shown in Fig. 1. The upper and lower blanks were fixed by the holder to the deforming die and the bottom die. The punch moved downward and pressed the upper blank against the lower blank. As the upper blank pushed the lower blank, both blanks were deformed locally and bonded together by the high surface pressure and large surface expansion. If the strength of the upper blank is weaker than the lower blank, it makes poor deformation of the lower blank. Thus, in this paper, steel sheet was applied to the upper blank and aluminum alloy sheet to the lower. The deforming die deforms itself properly during deformation and plays a part as a die which encloses the blanks moderately and mitigates the reduction in thickness of the blanks. The authors (Miwada et al., 2013) have confirmed that it acts so as to be advantageous to the bonding between steel and aluminum.

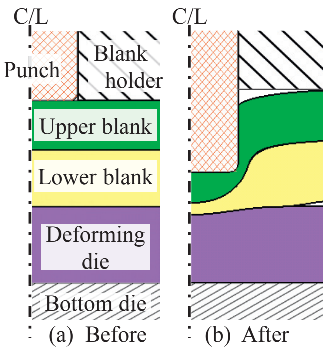

Fig. 1. Spot-bonding process.

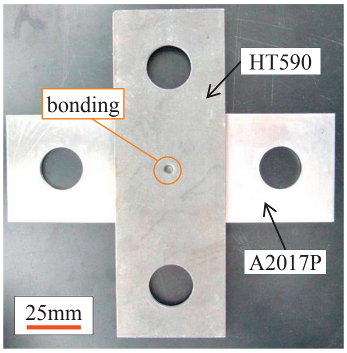

Fig. 2. Specimen of cross tension testing.

3. Experiments

3.1. Materials and experimental condition

A 590MPa-class high tensile strength steel sheet HT590 and cold rolled aluminum alloy sheet A2017P were used as blank material. The mechanical properties are shown in Table 1. Flow stress in Hollomon's equation was calculated from the results of compression test. Each sheet was cut in a length of 150 mm, a width of 50 mm and both sides of blank were perforated so as to fix the tool in cross tension testing. Blanks are treated with phosphate coating in order to improve interface lubrication. The contact surface between upper and lower blank was polished by emery paper #180 just before forging. The specimens were processed by 5.0 mm diameter punch in a form of cross specimen (see Fig. 2). The amount of the punch indentation was changed from 2.6 mm (thickness of upper blank) to 5.6 mm (total thickness of upper and lower blank).

3.2. Cross tension testing

Cross tension testing confirming ISO 14272 was conducted to evaluate joint strength. Joint strength was calculated by dividing the maximum load value by cross-section area of the punch. Maximum load and average joint strength for each condition with error bars representing standard deviations are shown in the Fig. 3. Joint strength became higher with the increase in the amount of punch indentation.

Table 1. Mechanical properties.

Material	Parts	Thickness / mm	Ultimate tensile strength / MPa	Flow stress / MPa	Vickers hardness
HT590	upper sheet	2.6	605	$\sigma = 1615\varepsilon^{0.31}$	194HV30
A2017P	lower sheet	3.0	461	$\sigma = 780\varepsilon^{0.28}$	126HV10
S25C	deforming die	8.0	—	$\sigma = 1252\varepsilon^{0.26}$	152HV30

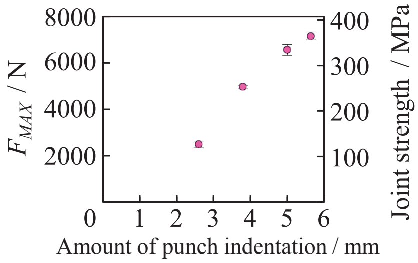

Fig. 3. Maximum load value and joint strength of each condition.

3.3. Investigation of fracture surface

Fracture surfaces of both blanks after cross tension testing were observed by SEM. Fractographs are shown in Fig. 4. They were compositional image in back scattered electron mode. Black area means aluminum alloy and white area indicates steel. With 2.6mm amount of punch indentation (thickness of upper blank) brittle fracture occurred at the interface and thin adhesion layer of opposite metal were observed on each surface sparsely. With 5.6mm (total thickness of upper and lower blank) breakage of steel base metal occurred. On the aluminum side, a lump of steel that peeled away from the surface of steel was left. Fracture mode was changed from interface fracture to base metal fracture when the amount of punch indentation was increased.

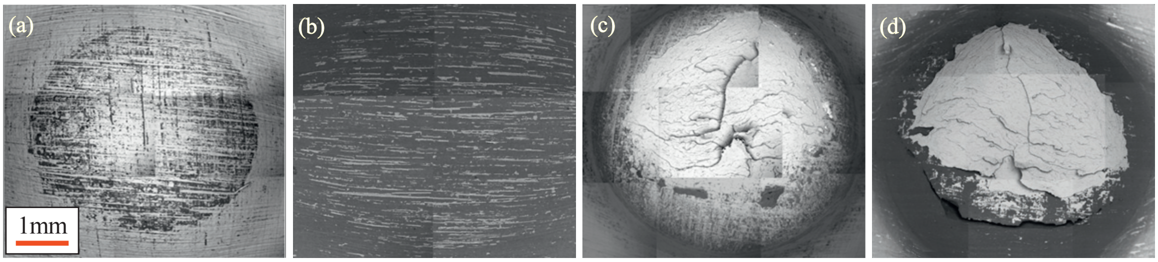

Fig. 4. Backscattered electron composition image of fracture surface of (a) HT590 with 2.6 mm amount of punch indentation, (b) A2017P with 2.6mm, (c) HT590 with 5.6mm, (d) A2017P with 5.6mm.

4. Finite element analysis

4.1. Analysis condition

In order to consider the deformation behavior during the spot-bonding process, finite element analysis was performed as axisymmetric problem by utilizing commercially simulation software DEFORM^{TM}-2D. Punch, blank holder, and bottom die were modeled as rigid. Upper blank, lower blank and deforming die were elasto-plastic model. The friction coefficient μ of the interfaces between tool and phosphate coated blanks was set to 0.1. On the other hand, it was set to the function of surface expansion ratio between polished blanks. When the surface expansion ratio is smaller than 2, friction share factor m was 0.55 and when the ratio is larger than 2, m was 1.00. These values were identified by the geometry fitting of simulation and experiment.

4.2. Analysis result and evaluation of the bonded region

A result of the changes in parameter's radius distribution outputting by tracking point spaced 0.1 mm apart at the contact surface during forging process are shown in Fig. 5. Surface expansion ratio of lower blank S_{Al}, maximum surface pressure p_{MAX}, and relative slippage x which calculated by time-integrating relative sliding velocity v of two blanks are shown in Fig. 5.(a), (b), (c) and (d) respectively. Radial distance from the center line r is set for the horizontal axis in all graphs. Surface expansion ratio S is defined by

$$S = A/A_0 \,, \tag{1}$$

where A_0 is the initial and A is the final area of the surface element. It was found that all four parameter values were increased when the amount of punch indentation was increased.

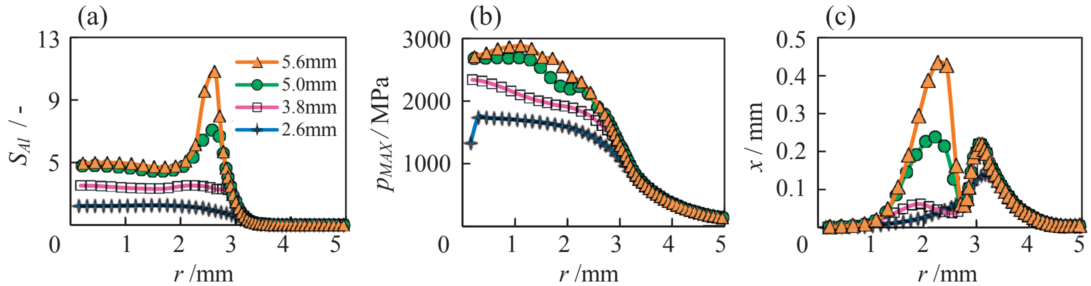

Fig. 5. Each parameter's distribution at joint interface during spot-bonding process; distribution of (a) lower blank surface expansion ratio S_{Al}, (b) maximum surface pressure p_{MAX}, (c) relative slippage of two blanks.

Besides, we attempted to evaluate the bonding region by utilizing the analysis results. In the case of solid phase bonding, it is necessary to put the surface energy to achieve bonding of two metals. The energy may cause the exposure of virgin metal by fracture of oxide film and contaminant cover layer, and the true contact by plastic deformation of microasperities. By inputting high surface energy, the contact surface became activated and the bond will be strong. Total friction work W is defined as a parameter evaluating the energy by friction force on the contact surface during the bonding process. W is calculated by time-integrating the product of friction share factor, surface pressure and relative velocity, and determines the amount of mechanical work per unit area. W is given by

$$W = \int mpv \, dt \,. \tag{2}$$

In addition, we also thought about the case in which large surface expansion occurred on each contact surface without relative slippage of blanks. Evaluation factor of real contact area Π is a dimensionless parameter evaluating the degree of real contact with virgin metals. It is defined as Π that the maximum value of the product of surface pressure and expansion ratio of aluminum alloy (lower) blank is divided by the 0.2 % proof stress of aluminum alloy. Π is given by

$$\Pi = (S_{Al}p)_{MAX}/\sigma_{0.2(Al)} \,. \tag{3}$$

The distribution of calculation result of W and Π during the process are shown in Fig. 6. Radial distance r is set for the horizontal axis. Both W and Π were also increased when the amount of the punch indentation is increased.

Furthermore, a result of investigating strong bonded region by utilizing these parameters is shown in Fig. 7. The curve means radius distribution with each amount of punch indentation, and the marks means fracture surface state. The information of fracture surface derived from SEM investigation was added on each mark. The marks were plotted in three categories, breakage of a base metal, adhesion and without anything. The graph shows that base metal fracture area is the region where both W and Π have large value. Hence it was able to confirm that large surface energy by friction force, surface expansion and surface pressure have a great influence on strong bonding. We concluded that predicting strong bonded region is possible by combined evaluation of two parameters.

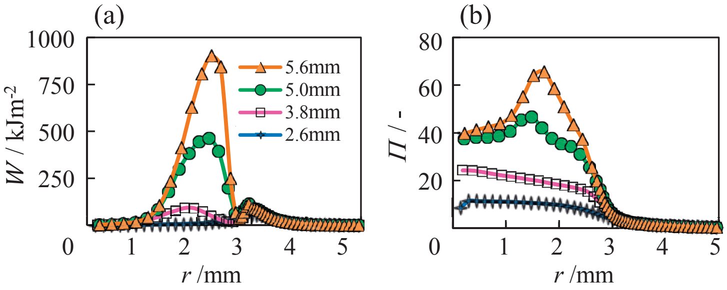

Fig. 6. Distribution of each parameter on contact surface; (a) total friction works W, (b) evaluation factor of real contact area Π.

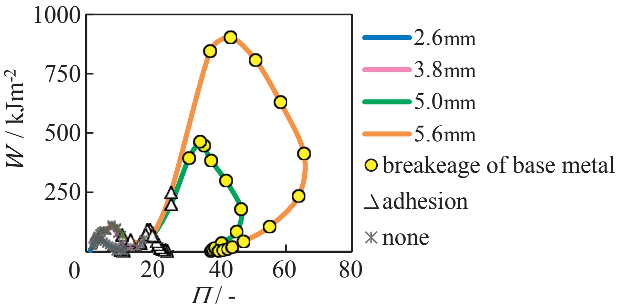

Fig. 7. Evaluation of bonded region on contact surface.

5. Conclusion

The authors applied the new bonding method by cold forge spot-bonding to the junction of high tensile strength steel and aluminum alloy sheet. In this study, by visualization of stress and deformation utilizing finite element analysis we revealed the bonding factor. The following results were obtained.

1) Joining of dissimilar metal sheets, 590MPa-class high tensile strength steel and A2017P aluminum alloy sheet, at room temperature was achieved by the application of cold forge spot-bonding method.
2) When the amount of punch indentation is increased, joint strength became higher. With the same depth of punch indentation as the upper blank thickness, brittle fracture occurred at the interface. With the same depth of punch indentation as the total thickness, breakage of steel base metal occurred.
3) Base metal fracture area is the region where both W evaluating the energy by friction force and Π evaluating the degree of real contact with virgin metals have large value.

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